Particle Ratios from Central Pb+Pb Collisions at the CERN SPS

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Abstract.

In this report, we will address the physics of K^-/K^+ and $\bar{p}/p$ ratios measured in 158 A·GeV Pb+Pb collisions, as a function of centrality and transverse momentum. We observe little significant centrality dependence in neither K^-/K^+ nor $\bar{p}/p$ ratios and they are almost constant as a function of P_t. In addition to the chemical freeze-out temperature T_{ch}, we extract the chemical potentials for both light and strange quarks (μ_q, μ_s) by comparing the present data with simple model predictions. The T_{ch} is greater than thermal freeze-out temperature which is extracted from transverse momentum distribution of charged hadrons.

Short title:

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1. Introduction

The physics goal of studying the ultra-relativistic heavy ion collisions is to understand the fundamental properties of matter under extreme conditions, i.e. high particle and energy densities. Particle ratios yields are useful source of information in studying the mechanism of particle production. In particular, one can study the details of chemical equilibrium in the collisions. Furthermore, the study is expected to be important in the search for the new form of matter: quark-gluon plasma.

A study of particle ratios will address the physics of particle production mechanism in high energy heavy ion collisions. In these collisions, one may expect that the beam energy is converted to particle creation and sidewards motion by many inelastic parton-parton collisions. The energy of beam makes the nucleus violent collisions. The state is in high temperature and/or high pressure. Hadronization occurs and hadrons collide with each other. Thus, there are particle creation and absorption. However, it is not sure whether the system is in chemical equilibrium or not. We can check the chemical equilibrium assumption by comparing particle ratios with model predictions. Later, particle creation and absorption stop and the system changes to random motion (thermal equilibrium). When the system becomes so big that the hadrons is free particle, the hadrons go out (thermal freeze-out). In SPS and AGS experiments, the transverse mass ($m_T = \sqrt{P_T^2 + m^2}$) distributions of hadrons suggest that there is local thermal equilibrium state and some indications of the transverse flow. The observed m_T distributions associated with the transverse flow picture give us the thermal freeze-out temperature T_{fo} and averaged transverse flow velocity $\langle v_T \rangle$.

We will show K^-/K^+ and $\bar{p}/p$ ratios as a function of centrality and transverse momentum from the NA44 experiment in central Pb+Pb collisions. The ratios will be compared with a simple model prediction of strange neutral hadron gas. The model predictions give us the value of chemical potential for light quark and strange quark (μ_q, μ_s) and chemical equilibrium temperature T_{ch}. The value of obtained T_{ch} is greater than T_{fo}.

2. NA44 experiment

The NA44 focusing spectrometer is designed to measure particle momentum distribution of charged hadrons around mid rapidity.

Fig. 1 is a schematic view of the NA44 focusing spectrometer. A Cherenkov beam counter (CX) provides the time of flight (TOF) start time. with a resolution of about 30ps [1], the total TOF resolution is less than 100ps. Particle identification is done by TOF and two different threshold Cherenkov counter; momentum resolution $\delta p/p$ is about 0.5% and the centrality is measured by the multiplicity counter behind the target.

Details about the spectrometer may be shown in [2, 3, 4].

3. Particle ratios and discussion

3.1. Lambda decay effect to proton ratios

In NA44 the charged hadrons are identified and their momentum measured $\approx$ 20m downstream from target. Thus, we have to estimate feed-down from Λ, Σ on the $\bar{p}/p$ ratio. We can not ignore these decayed particle effect. RQMD (ver 1.02) shows $\Lambda/p \approx 0.4$ around mid-rapidity in central Pb+Pb collisions.

We estimate the feed-down effect to $\bar{p}/p$ by parametrised particle distribution and a Monte Carlo simulation. The input of these simulation are parametrised dN/dy distributions and m_t slopes. dN/dy distributions for Λ, $\bar{\Lambda}$, p and $\bar{p}$ are taken from RQMD. Whereas the m_t slope parameters are from experimental result [5, 4].

The correction factor for measured proton distribution is given as a function of P_T and rapidity by:

$$C_p(P_T, y) = \frac{N_{p_{orig}}(P_T, y)}{N_{p_{orig}}(P_T, y) + N_{p_\Lambda}(P_T, y)} \tag{1}$$

where $N_{p_{orig}}$ is the number of proton from source (target) and N_{p_Λ} is the number of proton from Lambda decays. We can get 'pure proton' distribution by applying that factor to the measured proton distribution. The correction factor for anitiproton is given by the same method. To estimate the systematic error, we changed the absolute value of dN/dy for Λ, $\bar{\Lambda}$, p and $\bar{p}$ ($\pm$30%), respectively. The correction factor found to be about 0.9$\pm$0.1 and independent of P_T (See Fig. 2). The error is dominated by the systematic error and not by the errors of m_T slope.

3.2. K^-/K^+ and $\bar{p}/p$ ratio as a function of P_T and centrality

The NA44 experiment measures charged kaons and protons around mid-rapidity ($y_{lab} \approx$ 3). The event centrality $\sigma_{trig}/\sigma_{geom}$ is determined by a multiplicity counter behind target. We select three region; the most central 3.5%, further 3.5-6.0% and 6.0-8.5%. Fig. 3 shows K^-/K^+ and $\bar{p}/p$ ratios as a function of centrality and P_T. The top and bottom three figures are K^-/K^+ and $\bar{p}/p$ ratios as a function of P_T for each centrality region. The band in the figures indicates particle ratios in the acceptance. The $\bar{p}/p$ ratio in Fig. 3 does not include Lambda decay correction. As we discussed in the previous subsection, the Lambda decay does not affect to the P_T dependence. The general trend of these ratios is also almost constant as a function of P_T. We observe little centrality dependence in both K^-/K^+ and $\bar{p}/p$ ratios in the top 8.5% of the total geometrical cross section.

3.3. Strangeness neutral hadron gas model

Thermodynamics provides us chemical potential and chemical equilibrium temperature as physical variable to describe a system in chemical equilibrium. Chemical equilibrium state in heavy ion collisions is discussed in many paper, for example [6]-[17]. We introduce a simple model in this subsection, taken from Ref.[15].

If one assumes chemical equilibrium, the strangeness partition function of hadron gas is given by:

$$\ln Z_s^{HG} = \frac{V_h T^3}{2\pi^2}\Big[(\lambda_s\lambda_q^{-1} + \lambda_s^{-1}\lambda_q)\gamma_s F_K + (\lambda_s\lambda_q^2 + \lambda_s^{-1}\lambda_q^{-2})\gamma_s F_Y + (\lambda_s^2\lambda_q + \lambda_s^{-2}\lambda_q^{-1})\gamma_s^2 F_\Xi + (\lambda_s^3 + \lambda_s^{-3})\gamma_s^3 F_\Omega\Big] \qquad (2)$$

where γ_s is the strangeness saturation factor and λ_a is the fugasity of a quark ($a = q$: light quark, s : strange quark)

$$\lambda_a = \exp(\mu_a/T) \qquad (3)$$

μ_a is the chemical potential of a quark and T is the chemical equilibrium temperature. The phase space factor F is given by

$$F_A = \sum_j g_{A_j}(m_{A_j}/T)^2 K_2(m_{A_j}/T) \qquad (4)$$

where g is spin-isospin degeneracy factor and K_2 is the modified Bessel function. The suffix of F are kaon:K, hyperon:Y, cascade:Ξ and omega:Ω.

The suffix j means particles including higher resonance;

$$\begin{aligned} K_j &= K, K^*, ...m \leq 1780MeV \\ Y_j &= \Lambda, \Sigma, ...m \leq 1940MeV \\ \Xi_j &= \Xi, \Xi(1530), ...m \leq 1950MeV \\ \Omega_j &= \Omega, \Omega(2250) \end{aligned}$$

We can take one condition for Eq. 2. The total strangeness should be zero in the hadron gas because of strangeness conservation in the collisions.

$$\langle s\rangle - \langle\bar{s}\rangle = \lambda_s \frac{\partial}{\partial\lambda_s}\ln Z_S^{HG} = 0 \qquad (5)$$

This equation gives us μ_s as a function of μ_q for different T (See Fig. 4). We take $\gamma_s = 1$ (full strangeness equilibration) to calculate the potentials and the temperature.

K^-/K^+ and $\bar{p}/p$ ratios are described by μ_q, μ_s and T.

$$K^-/K^+ = \exp(-2(\mu_q - \mu_s)/T) \qquad (6)$$

$$\bar{p}/p = \exp(-6\mu_q/T) \qquad (7)$$

These expressions relate (μ_q, μ_s) to (K^-/K^+, $\bar{p}/p$) for different temperature.

3.4. comparison with model predictions

Fig. 5 shows K^-/K^+ vs. $\bar{p}/p$. The lines are model predictions of kaons and protons ratios for different temperature (150 to 200 MeV with 10 MeV step). The solid circle is from central Pb+Pb collisions from NA44. The open circle is NA52 minimum bias data around mid rapidity from Ref.[18].

The correction for Lambda decays for protons ratio is done for only NA44 data; the NA52 point may shift to smaller values, if a Lambda decay correction is considered.

The ratios is decreasing with increasing centrality, it is compatible with model predictions if chemical temperature is independent of the centrality. The chemical equilibrium temperature (T_{ch}) for NA44 data is found to be between 170 MeV and 180 MeV.

We calculate the chemical potentials for both point in case of $T_{ch} = 175$ MeV. $\mu_q = 81 \pm 3$ MeV, $\mu_s = 30 \pm 4$ MeV in Pb+Pb central collisions and $\mu_q = 64 \pm 2$ MeV, $\mu_s = 22 \pm 7$ MeV for minimum bias data.

3.5. Thermal freeze-out temperature

It is well known that the m_T distributions of hadrons in nuclear collisions show Boltzmann distribution:

$$\frac{1}{m_T}\frac{dN}{dm_T} = A \exp\left(\frac{-m_T}{T}\right) \tag{8}$$

where A is a arbitrary constant and T is slope parameter. If the system is in thermal equilibration state, T is independent of hadron mass. In p+p collisions, the T for charged pions, kaons and protons seem the same [19]. On the the hand, the T is increasing with hadron mass in S+S and Pb+Pb collisions. (See [20]). The trend of T in heavy ion collisions is discussed in [20]. The slope parameter T and particle mass m may be described by the relation ship: $T = T_{fo} + m\langle v_T\rangle^2$, where T_{fo} is thermal freeze-out temperature and $\langle v_T\rangle$ is averaged transverse flow velocity. Roughly speaking, T_{fo} shows thermal energy and $m\langle v_T\rangle^2$ shows kinetic energy of collective transverse flow. In the Ref. [20], the collision systems dependence of freeze-out temperature is discussed for p+p ($\sqrt{s} \approx 23$ GeV), S+S ($\sqrt{s} \approx 19.4$ A·GeV) and Pb+Pb ($\sqrt{s} \approx 17.2$ A·GeV). The freeze-out temperature is independent of the collision system in the CERN energy region and seems to saturate at $T_{fo} = 140 \pm 10$ MeV. It is lower than chemical equilibrium temperature, since the system has expanded

4. Summary

We report K^-/K^+ and $\bar{p}/p$ ratios as a function of P_T and centrality from Pb+Pb central collisions. Kaons and protons ratios are almost constant as a function of P_T. We observe little centrality dependence in either kaons and protons ratios. Assuming the system is in chemical equilibrium, the chemical equilibrium temperature is fond to be $T_{ch} \approx 175$ MeV for Pb+Pb. From K^-/K^+ and $\bar{p}/p$ ratios, the chemical potential of light and strange quark was calculated to be: $\mu_q \approx 80$ MeV and $\mu_s \approx 30$ MeV, respectively. The chemical equilibrium temperature is greater than the freeze-out temperature.

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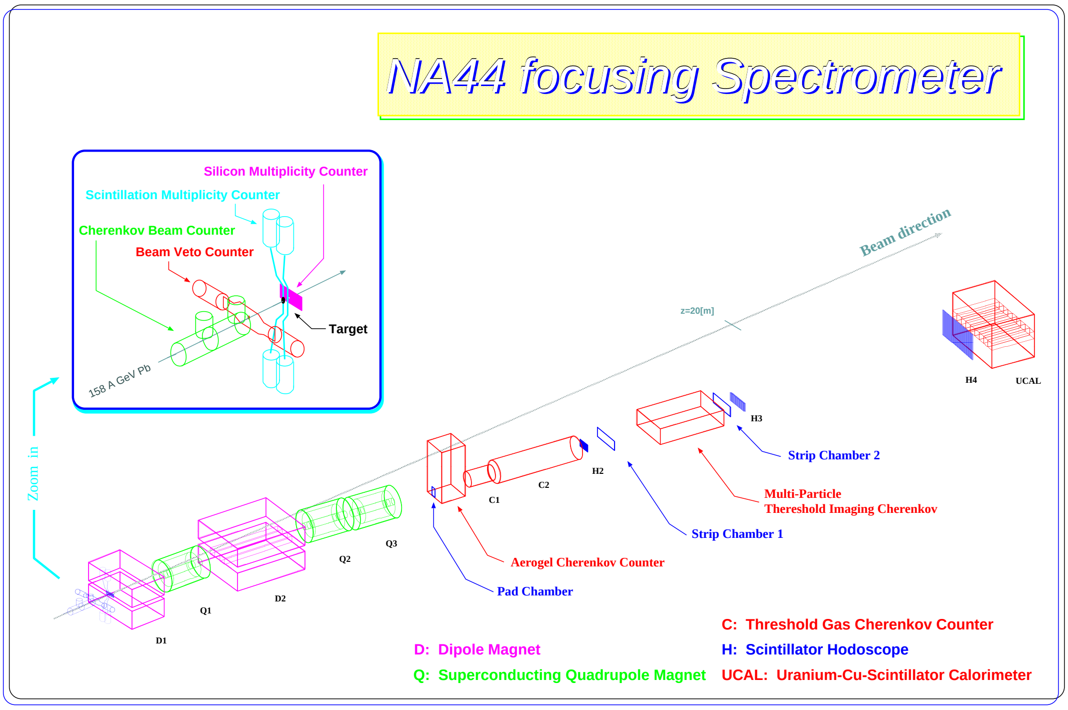
Fig. 1 Schematic view of the NA44 focusing spectrometer.

Fig. 2 Correction factor for $\bar{p}/p$ as a function of P_T.

Fig. 3 K^-/K^+ and $\bar{p}/p$ ratios as a function of centrality and P_T. Horizontal lines show the mean ratio.

Fig. 4 Correlation among μ_s, μ_q and T in strangeness neutral hadron gas. This correlation is a result of numerical calculation.

Fig. 5 Comparison with model predictions. The lines indicate kaon ratio as a function of proton ratios for different temperature (150 to 200 MeV with 10 MeV step).



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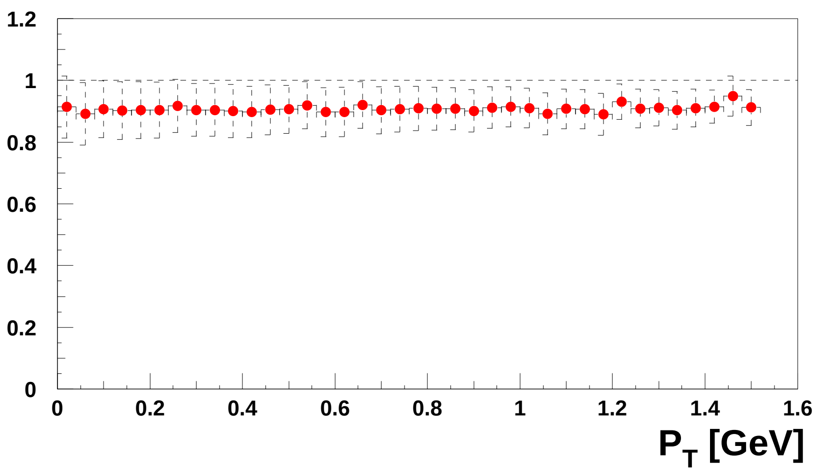
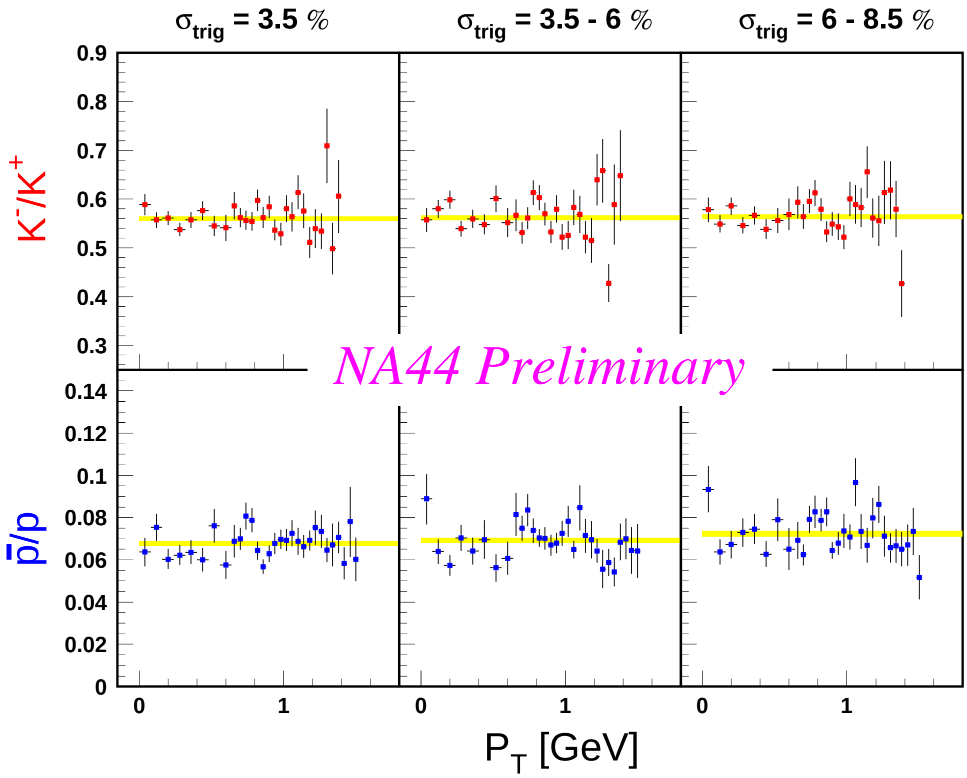


Figure 2. Correction factor for $\bar{p}/p$ as a function of P_T.



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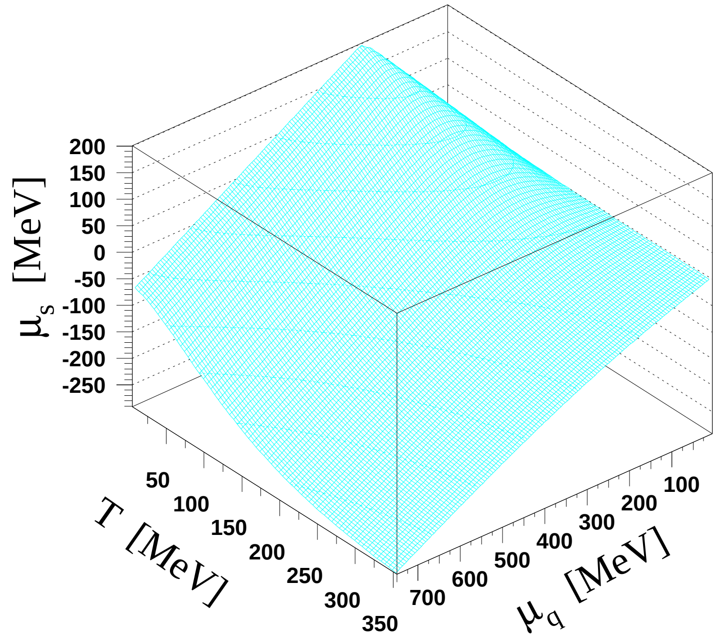

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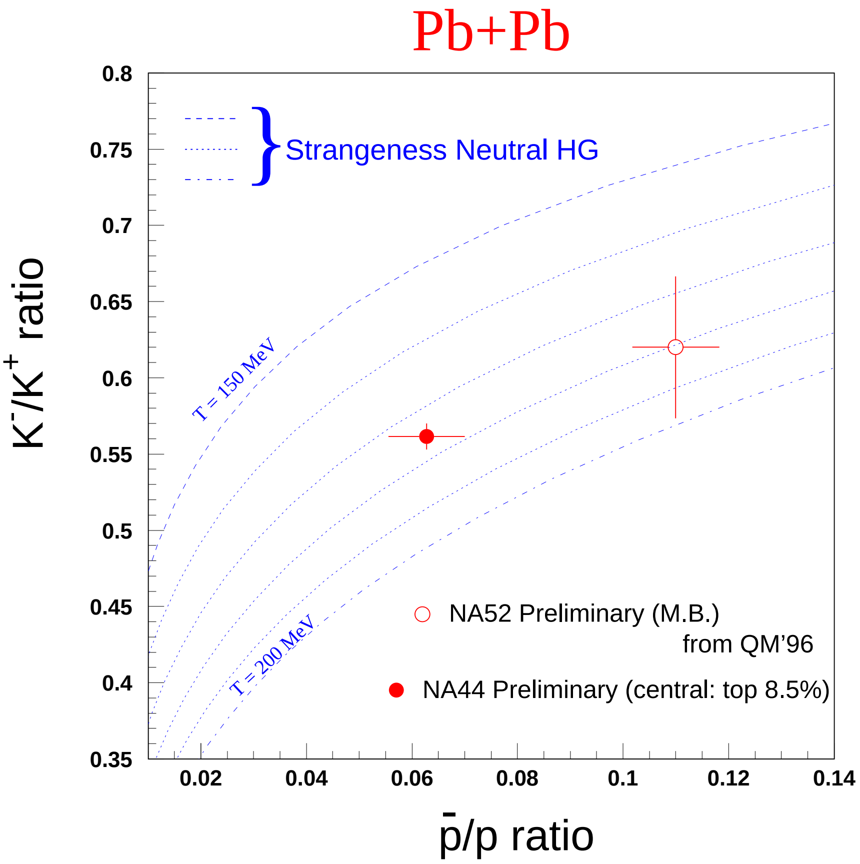

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